

X-RAY EMISSION FROM PSR J1809–1917 AND ITS PULSAR WIND NEBULA, POSSIBLY ASSOCIATED WITH THE  
TEV GAMMA-RAY SOURCE HESS J1809–193

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## ABSTRACT

We detected X-ray emission from the 50-kyr-old pulsar J1809–1917 and resolved its pulsar wind nebula (PWN) with the *Chandra X-ray Observatory*. The pulsar's observed flux is  $F_{\text{psr}} = (1.8 \pm 0.2) \times 10^{-14}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$  in the 1–6 keV band. A two-component blackbody+power-law (BB+PL) fit of the pulsar's spectrum yields the photon index  $\Gamma_{\text{psr}} = 1.2 \pm 0.6$  and luminosity  $L_{\text{psr}} = (4 \pm 1) \times 10^{31}$  ergs  $\text{s}^{-1}$  of the PL component, in the 0.5–8 keV band, for a plausible distance  $d = 3.5$  kpc and  $n_{\text{H}} = 0.7 \times 10^{22}$   $\text{cm}^{-2}$ . The BB component corresponds to the temperature  $T \approx 2$  MK, and bolometric luminosity  $L_{\text{bol}} \sim 1 \times 10^{32}$  ergs  $\text{s}^{-1}$ . The bright inner PWN component of a  $3'' \times 12''$  size is elongated in the north-south direction, with the pulsar close to its south end. This component is immersed in a larger ( $\approx 20'' \times 40''$ ), similarly elongated outer PWN component of lower surface brightness. The elongated shape of the compact PWN can be explained by the ram pressure confinement of the pulsar wind due to the supersonic motion of the pulsar. The observed flux of the compact PWN, including both components, is  $F_{\text{pwn}} \simeq (1.5 \pm 0.1) \times 10^{-13}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$  in the 1–6 keV band. The PWN spectrum can be fitted with a PL model with  $n_{\text{H}} \approx 0.7 \times 10^{22}$   $\text{cm}^{-2}$  and photon index  $\Gamma_{\text{pwn}} = 1.4 \pm 0.1$ , corresponding to the 0.5–8 keV luminosity  $L_{\text{pwn}} \approx 4 \times 10^{32}$  ergs  $\text{s}^{-1}$ . The compact PWN appears to be inside a more extended ( $\approx 4' \times 4'$ ) emission with the total observed flux  $F_{\text{ext}} \sim 5 \times 10^{-13}$  ergs  $\text{s}^{-1}$  in the 0.8–7 keV band. This large-scale emission is more extended to the south of the pulsar, i.e. in the direction of the alleged pulsar motion. To explain the extended X-ray emission ahead of the moving pulsar, one has to invoke strong intrinsic anisotropy of the pulsar wind or assume that this emission comes from a relic PWN swept by the asymmetrical reverse SNR shock. The pulsar and its PWN are located within the extent of the unidentified TeV source HESS J1809–193. The brightest part of the TeV source is offset by  $\sim 8'$  to the south of the pulsar, i.e. in the same direction as the large-scale X-ray emission. Although the association between the PSR J1809–1917 and HESS J1809–193 is plausible, an alternative source of relativistic electrons powering HESS J1809–193 might be the serendipitously discovered X-ray source CXOU J180940.7–192544. In addition to the CMBR or Galactic starlight background, the low-frequency seed photons for Compton upscattering to TeV energies might be supplied by bright infrared emission from dust-molecular clouds seen within HESS J1809–193.

*Subject headings:* pulsars: individual (PSR J1809–1917) — X-rays: individual (CXOU J180940.7–192544, CXOU 180933.3–192959) — gamma-rays: individual (HESS J1809–193) — ISM: individual (IRAS 18067–1927, IRAS 18067–1921)

## 1. INTRODUCTION

*Chandra* and *XMM-Newton* observations have established the ubiquity of X-ray pulsar wind nebulae (PWNe) around young rotation-powered pulsars (see the reviews by Kaspi et al. 2006 and Gaensler & Slane 2006). The X-ray PWN emission is produced by relativistic particles gyrating in the magnetic field downstream of the termination shock in the pulsar wind (Kennel & Coroniti 1994; Arons 2004). Most of the PWNe have been discovered around young ( $\tau \lesssim 30$  kyr) pulsars. The innermost parts of the young PWNe often show axisymmetric morphologies, including toroidal structures and jets along the pulsar's spin axis. Recently, it has become apparent that PWNe accompanying older pulsars can also be quite luminous (e.g., McGowan et al. 2006). Many of these older PWNe exhibit cometary morphologies indicating that the pulsar wind is confined by the ram pressure caused by the supersonic motion of the pulsar in the ambient medium. Studying X-ray PWNe of various ages helps understand the nature and evolution of the ultrarelativistic pulsar winds and their interaction with the ambient medium.

An interesting object for such investigations is PSR J809–

1917 (hereafter J1809). The discovery of this radio pulsar ( $P = 82.7$  ms) in the Parkes Multibeam Pulsar Survey<sup>1</sup> was reported by Morris et al. (2002). The pulsar's dispersion measure,  $\text{DM} = 197 \text{ cm}^{-3} \text{ pc}$ , and the Galactic electron distribution models by Taylor & Cordes (1993) and Cordes & Lazio (2002) give the distance to the pulsar of 3.7 and 3.5 kpc, respectively. Having the spin-down age  $\tau \equiv P/2\dot{P} = 51$  kyr and spin-down power  $\dot{E} \equiv 4\pi^2 I \dot{P}^3 \simeq 1.8 \times 10^{36}$  ergs  $\text{s}^{-1}$ , J1809 is somewhat older and less energetic than the famous Vela pulsar ( $\tau = 11$  kyr,  $\dot{E} = 6.9 \times 10^{36}$  ergs  $\text{s}^{-1}$ ), which is accompanied by a remarkable PWN resolved in radio (Dodson et al. 2003b) and X-rays (Pavlov et al. 2003, and references therein). However, it is much more energetic than typical “middle-aged” pulsars, such as B0656+14 ( $\tau = 110$  kyr,  $\dot{E} = 3.8 \times 10^{34}$  ergs  $\text{s}^{-1}$ ) and Geminga ( $\tau = 340$  kyr,  $\dot{E} = 3.2 \times 10^{34}$  ergs  $\text{s}^{-1}$ ), whose PWNe are very faint (e.g., Pavlov et al. 2006).

J1809 is young enough to look for a remnant of the supernova that created the pulsar. Deep radio observations by Brogan et al. (2004) have revealed two compact HII regions and two SNRs, G11.03–0.05 and G11.18+0.11, projected near the pulsar (the pulsar's Galactic coordinates are  $l = 11.094^\circ$ ,

$b = +0.080^\circ$ ). The distances to the SNRs, estimated from the radio surface brightness-diameter ( $\Sigma - D$ ) relation (Case & Bhattacharya 1998), are  $\sim 16$  and  $\sim 17$  kpc, respectively. However, given the very large uncertainty of the  $\Sigma - D$  relation for faint SNRs, the association of J1809 with one of the SNRs cannot be ruled out despite the discrepant distance estimates. Brogan et al. (2004) estimated that the pulsar would need to have the transverse speed of about 200 or 140 km s $^{-1}$  to originate from the geometrical center of G11.03–0.05 or G11.18+0.11, respectively, assuming that all three are at the same distance of 4 kpc and the pulsar's true age is 50 kyr. The estimated speeds are close to the average speeds recently measured for a large sample of radio pulsars by Hobbs et al. (2005).

Before the detailed radio studies were carried out, the region had been observed by *ASCA*, first as part of the Galactic plane survey (Sugizaki et al. 2001), and then with a deeper follow-up exposure (Bamba et al. 2003; Ueno et al. 2005). These observations revealed an amorphous diffuse emission that encompassed the pulsar position. No pulsar has been detected in these X-ray observations. The observed large-scale emission was attributed to a new SNR, dubbed G11.0+0.0. Bamba et al. (2003) have found that the X-ray spectrum of the putative SNR fits the absorbed power-law (PL) model with photon index  $\Gamma = 1.6^{+0.3}_{-0.2}$ , hydrogen column density  $n_{\text{H},22} \equiv n_{\text{H}}/(10^{22} \text{ cm}^{-2}) = 0.8 \pm 0.3$ , and 0.7–10 keV flux of  $3.8 \times 10^{-12}$  ergs cm $^{-2}$  s $^{-1}$ . Using the best-fit  $n_{\text{H}}$  and assuming that the mean density in the Galactic plane is 1 H cm $^{-3}$ , Bamba et al. (2003) estimated the distance of 2.6 kpc, which gives the X-ray luminosity of  $\approx 3.7 \times 10^{33}$  ergs s $^{-1}$  (in 0.7–10 keV). These authors suggested that G11.0+0.0 could be a Crab-like (plerionic) SNR.

Studying of the J1809 field has become particularly interesting after the recent discovery of the TeV  $\gamma$ -ray source HESS J1809–193 (hereafter HESS J1809; Aharonian et al. 2007). The brightest, firmly detected part of this extended source (radius  $\sim 12' - 15'$ ) is centered at R.A. = 18 $^{\text{h}}09.8^{\text{m}}$ , decl. =  $-19^{\circ}25'$ , about 8' from J1809; its  $\gamma$ -ray flux is  $F_{\gamma} \approx 1.4 \times 10^{-12}$  ergs cm $^{-2}$  s $^{-1}$  in the 1–10 TeV band. Given the small angular separation, it seems plausible that the HESS source could be powered by this pulsar, in which case its  $\gamma$ -ray luminosity,  $L_{\gamma} \approx 2 \times 10^{34} d_{3.5}^2$  ergs s $^{-1}$ , would be about 1% of the pulsar's spindown power.

In this paper, we describe the results of a *Chandra* observation of PSR J1809–1917 and its compact synchrotron nebula<sup>2</sup> and discuss its possible connection to HESS J1809. We also describe the multiwavelength properties of objects located within the central part of HESS J1809, including two newly discovered X-ray sources, and discuss their relation to HESS J1809. The details of the observation and the data analysis are presented in §2. In §3 we discuss possible interpretations of the PWN morphology, describe inferences from the pulsar spectrum, and speculate on the nature of HESS J1809 and its relation to the other sources in the field. Our main results are summarized in §4.

## 2. OBSERVATIONS AND DATA ANALYSIS

J1809 was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board *Chandra* on 2004 July 21 (ObsID 3853). The useful scientific exposure time was 19,955 s. The observation was carried out in Faint mode, and the pul-

sar was imaged on S3 chip,  $\approx 0.72'$  off-axis. The other ACIS chips activated during this observation were S1, S2, S4, I2, and I3. The detector was operated in Full Frame mode, which provides time resolution of 3.24 seconds. The data were reduced using the Chandra Interactive Analysis of Observations (CIAO) software (ver. 3.2.1; CALDB ver. 3.0.3).

### 2.1. Images

Figure 1 shows the ACIS-S3 image of the region around J1809. An extended X-ray source is clearly seen in the image around R.A. = 18 $^{\text{h}}09^{\text{m}}43.123^{\text{s}}$ , decl. =  $-19^{\circ}17'38.17''$  (these are the coordinates of the center of the brightest pixel). The difference of 0.5'' between this position and the radio position from Morris et al. (2006) is within the uncertainty of absolute *Chandra* astrometry (0.6'' at the 90% confidence level). The close match between the X-ray and radio positions and the extended morphology of the observed X-ray emission allow us to conclude that we detected the X-ray emission from J1809 and its PWN.

The brighter *inner PWN* component of an  $\approx 12'' \times 3''$  size (i.e.  $0.2 \times 0.05$  pc $^2$  at  $d = 3.5$  kpc) is elongated along the approximate symmetry axis (position angle  $\approx 14^\circ$  east of north). The linear profile of the surface brightness distribution along the symmetry axis, extracted with the  $4.9'' \times 0.49''$  (i.e.  $10 \times 1$  pixels) sliding box, is shown in Figure 2. The inner PWN is surrounded by a similarly elongated  $\sim 20'' \times 40''$  “halo” of lower surface brightness, which we will call the *outer PWN* component (see Fig. 1, *top*). In addition to these two relatively compact components, the heavily binned and smoothed image (see Fig. 1, *bottom right*, and Fig. 3a) reveals even fainter large-scale *extended emission*, concentrated at the lower half of the S3 chip (south of the pulsar). The morphology of this emission (see also the *ASCA* image in Fig. 3c) indicates that it possibly extends further south but may not be discernible on the S2 chip because of its lower sensitivity.

The only source on the S2 chip detected above the  $3\sigma$  level is located at R.A. = 18 $^{\text{h}}09^{\text{m}}40.725^{\text{s}}$ , decl. =  $-19^{\circ}25'44.10''$  (the  $1\sigma$  centroid uncertainty is 0.28'' and 0.29'' in right ascension and declination, respectively), well within the brightest central part of HESS J1809 (about 2' west of the peak of the TeV brightness distribution; see Fig. 3). We designate this source CXOU J180940.7–192544 and call it Ch1 hereafter. Although Ch1 appears to be extended in the ACIS image, the point spread function (PSF) simulation shows that this is likely the result of the off-axis location (off-axis angle  $\theta = 7.4'$ ). We find no significant large-scale non-uniformities in the X-ray background on the S2 chip (see Fig. 3).

We have also examined the S1 chip image and found only one source detected above the  $3\sigma$  level. The source, CXOU 180933.3–192959 (hereafter Ch2), is located at R.A. = 18 $^{\text{h}}09^{\text{m}}33.336^{\text{s}}$ , decl. =  $-19^{\circ}29'59.89''$  (the  $1\sigma$  centroid uncertainty is 0.70'' in R.A. and 0.74'' in decl.), which is about 6' from the center of HESS J1809. The X-ray source is consistent with being point-like; however, due to the broadened PSF (FWHM  $\approx 10''$ ) at the large off-axis angle (11.8'), a compact extended source cannot be ruled out. We have also searched for diffuse emission features on the S1 chip and produced an image corrected for the exposure map non-uniformities (see Fig. 3b). In this image the X-ray emission is systematically brighter toward the western edge of the S1 chip, likely due to the imperfection of the monoenergetic (2 keV) exposure map correction at large off-axis angles (see, however, §2.5). We found no traces of the radio SNRs G11.03–0.05 and G11.18+0.11 in the ACIS images

<sup>2</sup> Preliminary results of this observation have been presented by Sanwal et al. (2005).

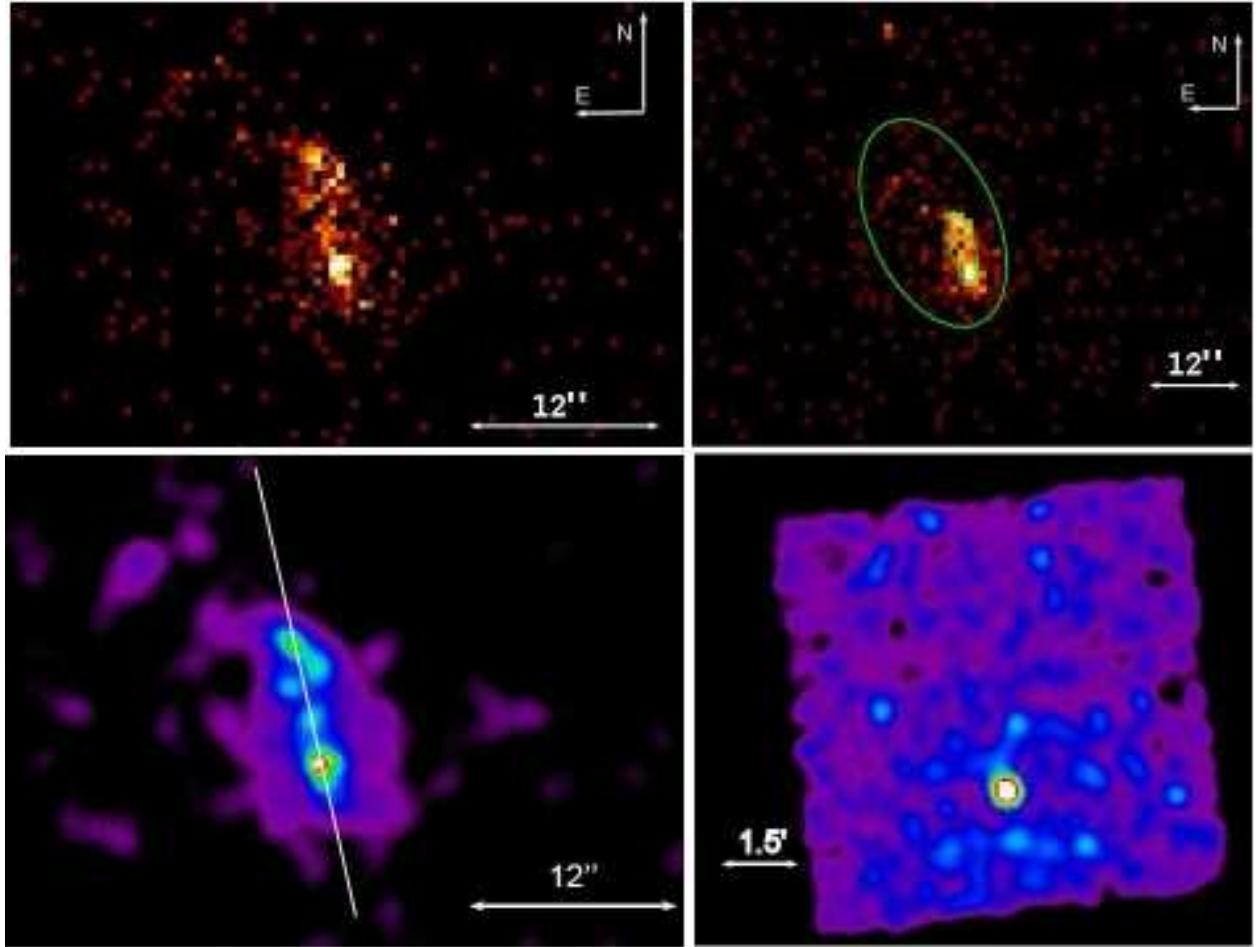


FIG. 1.— *Top left:* ACIS-S3 image of J1809 and its PWN (0.8–7 keV; pixel size 0.49''). *Top right:* Extraction regions used for the analysis of the PWN components (0.8–7 keV; pixel size 0.98''). *Bottom left:* Adaptively smoothed sub-pixel resolution image (0.8–7 keV; pixel size 0.25'') obtained by removing the pipeline pixel-randomization and applying the sub-pixel resolution tool (based on analyzing the charge distribution produced by an X-ray event; Tsunemi et al. 2001; Mori et al. 2001). The straight line shows the approximate symmetry axis of the X-ray PWN. *Bottom right:* Heavily binned (pixels size 3.94'') and smoothed (with a gaussian kernel of  $r = 25''$ ) ACIS-S3 image of J1809 and its PWN. The brightness and smoothing scales are chosen to show the fainter, more extended emission.

(see Fig. 3).

## 2.2. Spectral analysis

### 2.2.1. PWN spectrum

We extracted the PWN spectra from two elliptical regions shown in Figure 1 (*top right*). The smaller elliptical region (of 25.1 arcsec<sup>2</sup> area) encompasses the brighter inner PWN, while the larger elliptical region (of 399.4 arcsec<sup>2</sup> area) includes the outer PWN component of a lower surface brightness. To avoid the contamination of the PWN spectrum by the pulsar, we excluded from these regions the circular region of 1.46'' radius centered on the brightest pixel. The background (367 counts in 5202 arcsec<sup>2</sup> area, 0.3–8 keV band) was measured from the 37'' <  $r$  < 55'' annulus centered on the pulsar. The total numbers of counts extracted from the smaller and larger elliptical regions (excluding the 1.46'' radius circle) are 153 and 365, of which 99.2% and 92.4% are expected to come from the source, which gives  $151 \pm 12$  and  $337 \pm 19$  PWN counts in the two regions. The observed PWN fluxes (in the 1–6 keV band) are  $F_{\text{inner}} = (8.1 \pm 0.7) \times 10^{-14}$  and  $F_{\text{pwn}} = (14.7 \pm 0.8) \times 10^{-14}$  ergs s<sup>-1</sup> cm<sup>-2</sup> for the inner and the entire (inner+outer) PWN, respectively. The corresponding average intensities are  $I_{\text{inner}} = (4.4 \pm 0.4) \times 10^{-15}$  and  $I_{\text{pwn}} = (3.7 \pm 0.2) \times 10^{-16}$  ergs cm<sup>-2</sup> s<sup>-1</sup> arcsec<sup>-2</sup>.

To investigate the PWN spectral properties, we first fit the

spectra for each of the two PWN regions with the absorbed PL model, allowing the hydrogen column density,  $n_{\text{H}}$ , to vary. These fits result in spectral slopes  $\Gamma_{\text{pwn}} \approx 1.2\text{--}2.0$  and  $n_{\text{H},22} \sim 0.5\text{--}1.1$  (the ranges correspond to the 68% confidence level for a single interesting parameter). The difference in the best-fit parameters for the inner and the entire PWN (see Fig. 4) is statistically insignificant. In particular, we see no spectral softening (expected due to synchrotron cooling) in the spectrum extracted from the larger region (entire PWN) compared to the spectrum of the inner PWN<sup>3</sup>. Therefore, below we will use the better constrained best-fit parameters for the entire PWN (see Figs. 5 and 6) whenever we refer to the PWN spectral properties.

Given the J1809's dispersion measure,  $\text{DM} = 197 \text{ cm}^{-3} \text{ pc}$  (i.e., electron column density  $n_e = 6.08 \times 10^{20} \text{ cm}^{-2}$ ), the  $n_{\text{H},22}$  value of 0.72 (obtained from the fit to the spectrum of the entire PWN) corresponds to the ISM ionization degree  $n_e/n_{\text{H}} \approx 8.4\%$ , only slightly below the commonly used value of 10%, which corresponds to  $n_{\text{H},22} = 0.61$ . The total Galactic HI column density in this direction is  $1.8 \times 10^{22} \text{ cm}^{-2}$  (Dickey

<sup>3</sup> We have also measured the spectrum of the outer PWN separately and found that the best-fit PL parameters are consistent with those obtained for the inner PWN and the entire PWN spectra, but their uncertainties are larger because of the larger background contribution.

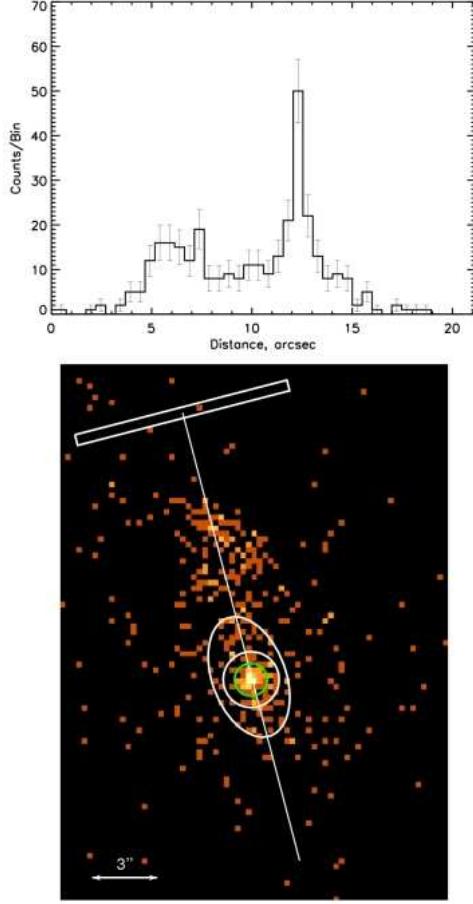


FIG. 2.— *Top*: One-dimensional surface brightness distribution along the symmetry axis of the J1809 PWN. *Bottom*: Extraction regions used to measure the pulsar's spectrum (see §2.2.2) and the sliding box used for measuring the one-dimensional surface brightness distribution (see §2.1 for details).

& Lockman, 1990).

The isotropic luminosity of the entire (inner+outer) X-ray PWN is  $L_{\text{pwn}} \equiv 4\pi d^2 F_{\text{pwn}}^{\text{unabs}} \approx (3.9 \pm 0.3) \times 10^{32} d_{3.5}^2 \text{ ergs s}^{-1}$  in the 0.5–8 keV band ( $d_{3.5} = d/3.5 \text{ kpc}$ ), with approximately equal contributions from the outer and the inner PWN components (see Table 1).

We have also attempted to fit the spectrum of the faint large-scale emission (within the ellipse shown in Fig. 3a, excluding the compact PWN; 13.2 arcmin<sup>2</sup> area) surrounding J1809 and its compact PWN. Because of the low surface brightness of this emission and large background contribution ( $\sim 65\%$ ), the spectral fits yield inconclusive results. With the absorption being fixed at  $n_{\text{H},22} = 0.72$ , the fits with single PL and thermal plasma<sup>4</sup> models give  $\Gamma = 2.3 \pm 0.3$  ( $\chi^2_{\nu} \approx 2$ ) and  $kT = 0.67 \pm 0.08 \text{ keV}$ , ( $\chi^2_{\nu} \approx 3$ ). The main contribution to the large values of  $\chi^2_{\nu}$  comes from high-energy channels ( $\gtrsim 4 \text{ keV}$  and  $\gtrsim 2 \text{ keV}$  for PL and mekal, respectively), which suggests either a mixture of thermal and hard non-thermal emission or varying  $\Gamma$  or  $kT$  within the extraction region. The measured flux, independent of the model, is  $F_{\text{ext}} \sim 5 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}$  in the 0.8–7 keV band, corresponding to the average surface brightness  $I_{\text{ext}} \sim 1 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$ . The unabsorbed flux, obtained from the PL model, is  $F_{\text{ext}}^{\text{unabs}} \sim 8 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}$  in the 0.5–8 keV band.

<sup>4</sup> The model “mekal” in XSPEC, with standard abundance

TABLE 1  
PL FITS TO THE PWN SPECTRUM

Model	$n_{\text{H},22}$	$\mathcal{N}^a$	$\Gamma$	(C or $\chi^2$ ) <sup>b</sup> /dof	$L_{\text{X}}^c$
Entire PWN	0.72	$35.6_{-3.8}^{+4.6}$	$1.41_{-0.11}^{+0.12}$	0.82/34	$3.89_{-0.27}^{+0.24}$
Inner PWN	0.98	$30.6_{-4.6}^{+5.3}$	$1.85_{-0.17}^{+0.17}$	335/526	$2.21_{-0.17}^{+0.19}$

NOTE. — The fits are for fixed  $n_{\text{H},22} \equiv n_{\text{H}}/10^{22} \text{ cm}^{-2}$ . The uncertainties are given at 68% confidence level for a single interesting parameter.

<sup>a</sup>Spectral flux in units of  $10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$  at 1 keV.

<sup>b</sup>We use the C statistic (Cash 1979) for the inner PWN (which has less counts) and the  $\chi^2$  statistic for the entire PWN.

<sup>c</sup>Unabsorbed isotropic luminosity in the 0.5–8 keV band, in units of  $10^{32} \text{ ergs s}^{-1}$ .

### 2.2.2. Pulsar spectrum

To minimize the contamination by the PWN, the pulsar spectrum was extracted from a small circular aperture (green circle in the bottom panel of Fig. 2) with the radius of 1.5 ACIS pixels ( $\simeq 0.74''$ , 85% encircled energy radius), while the background was taken from the 10 arcsec<sup>2</sup> region between the white circle and white ellipse in the bottom panel of Fig. 2. The background region includes the bright part of the PWN; it contributes  $\approx 8$  counts to the total of 67 counts extracted from the source aperture. Given the small number of counts and the large background contribution, we chose not to subtract the background but rather to fit it simultaneously with the source spectrum, using an additional absorbed PL model with the same  $n_{\text{H}}$  as for the source. The pulsar's absorbed flux is  $F_{\text{psr}} = (1.8 \pm 0.2) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$  in the 1–6 keV band (aperture corrected).

Although the absorbed PL model formally fits the pulsar spectrum indicating a soft PL ( $\Gamma_{\text{psr}} \approx 2.6$ ; see Table 2 and Figs. 7 and 8), the fit yields  $n_{\text{H},22} \approx 0.4$ , smaller than that for the PL fit to the entire PWN spectrum. To obtain a better constrained fit, we fixed the hydrogen column density at  $n_{\text{H},22} = 0.72$ , obtained above from the PL fit to the PWN spectrum. With this  $n_{\text{H}}$ , the single PL fit is still acceptable, but it yields a large photon index,  $\Gamma = 3.2 \pm 0.4$ , suggesting a thermal emission contribution. A two-component, BB+PL, fit yields reasonable values of fitting parameters (see Table 2 and Figs. 7–9), which, however, are poorly constrained because of the small number of photons detected. The slope of the PL component is  $\Gamma_{\text{psr}} = 1.2 \pm 0.6$ , and its unabsorbed luminosity is  $L_{\text{psr}} \sim 4 \times 10^{31} d_{3.5}^2 \text{ ergs s}^{-1}$  in the 0.5–8 keV band. The temperature and the projected area of the BB component are strongly correlated (see Fig. 9), which results in large uncertainties for these parameters. The best-fit temperature for the BB component is  $T \approx 2 \text{ MK}$ , while the projected emitting area,  $\mathcal{A} \sim 3 \times 10^6 d_{3.5}^2 \text{ m}^2$ , is smaller than that of the surface of a neutron star ( $\pi R^2 \sim 3 \times 10^8 \text{ m}^2$ ), but larger than the conventional polar cap area  $A_{\text{pc}} = 2\pi^2 R^3/cP \approx 2.5 \times 10^5 \text{ m}^2$ . The corresponding bolometric luminosity,  $L_{\text{bol}} \equiv 4\mathcal{A}\sigma T^4 \sim 1 \times 10^{32} d_{3.5}^2 \text{ ergs s}^{-1}$ .

### 2.2.3. Ch1 spectrum

We extracted 99 events from the elliptical region (with the semi-major and semi-minor axes of  $10.3''$  and  $6.3''$ , respectively) centered on the best-fit position of Ch1 and conforming to the shape of the off-axis PSF. Based on the PSF simulation, the extraction region contains  $\approx 95\%$  of point source counts. The expected background contribution, 4.4 counts, is negligible ( $\approx 4\%$  of the total number of counts). The measured source flux in 0.8–7 keV is  $F_{\text{Ch1}} = (8.6 \pm 0.9) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ , after correcting for vignetting and finite extrac-

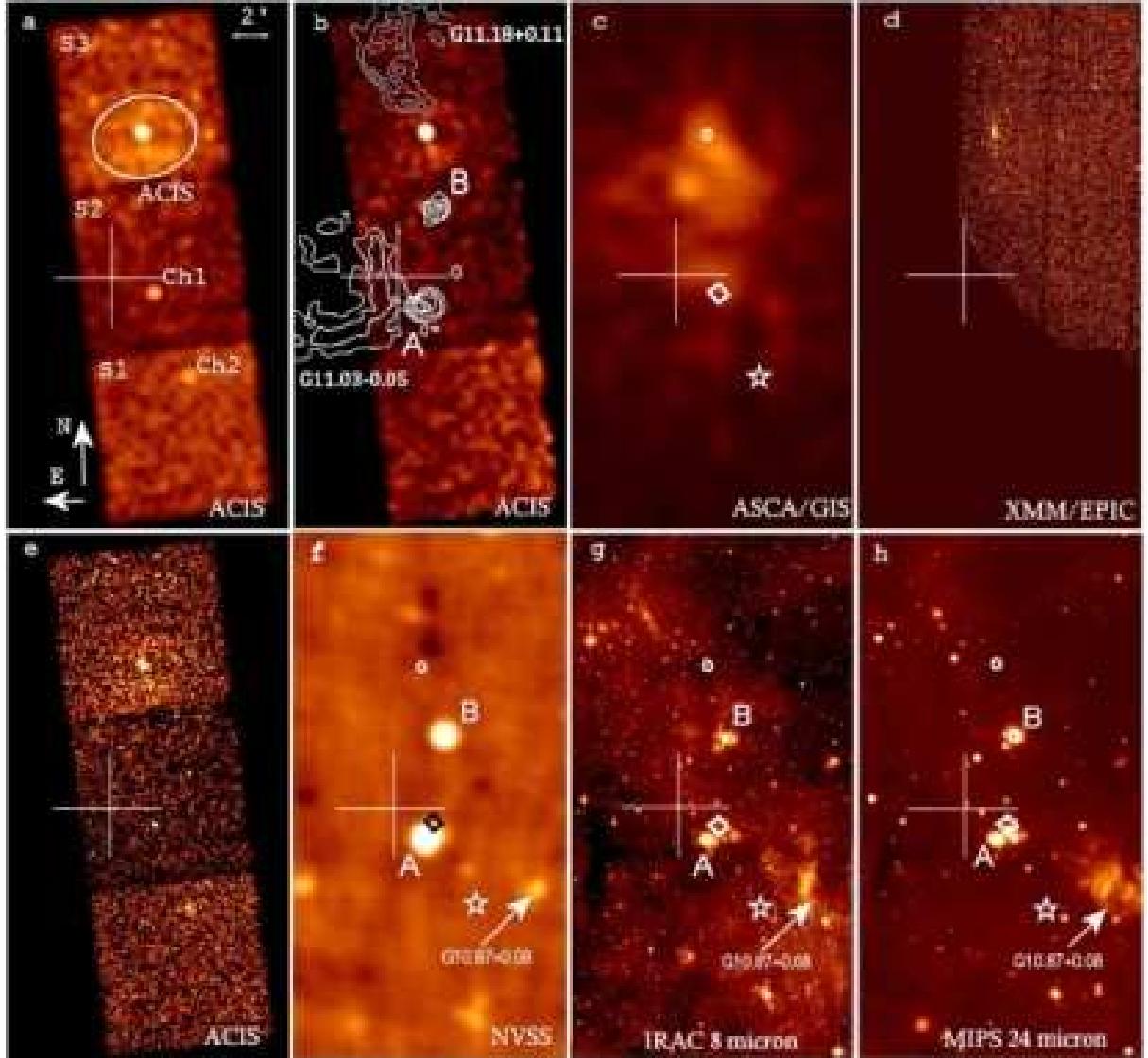


FIG. 3.— J1809 and its vicinity at different wavelengths. All the eight panels show the same area on the sky. *a*: ACIS-S3, S2 and S1 images (0.8–7 keV; smoothed with  $23.6''$  gaussian kernel). The white ellipse shows the region used to estimate the flux of the large-scale diffuse emission (see §2.2.1). *b*: The same image divided by the exposure map with point sources removed (except for J1809). The contours show the radio emission from two SNRs and two compact (possibly HII) regions (labeled A and B; adopted from Brogan et al. 2004). *c*: ASCA GIS2 and GIS3 combined image (39 ks total exposure; 0.5–10 keV) of the same region (the image has been divided by the exposure map; astrometry has been corrected, courtesy of E. Gotthelf). *d*: Combined 9 ks EPIC-PN and MOS1+2 image (0.5–10 keV) obtained in the Galactic plane survey (PI: R. Warwick). *e*: The same as in the *panel a* with no smoothing applied (pixel size is  $7.4''$ ). *f*: NRAO VLA Sky Survey (NVSS; Condon et al. 1998) image at 1.4 GHz. *g*: Spitzer IRAC 8  $\mu$ m image from the GLIMPSE survey. *h*: Spitzer MIPS 24  $\mu$ m image. The white circle in *panels c, f, g*, and *h* marks the position of the pulsar, the diamond and the star mark the Ch1 and Ch2 positions, respectively, and the cross shows the position of the TeV brightness distribution of HESS J1809.

TABLE 2  
FITS TO THE PULSAR SPECTRUM

Model	$n_{\text{H},22}$	$\mathcal{N}^a$ or $\mathcal{A}^b$	$\Gamma$ or $kT^c$	$C$	$L_X^d$ or $L_{\text{bol}}^e$
PL	0.72	$22.6^{+4.9}_{-4.2}$	$3.22^{+0.42}_{-0.38}$	412	$0.98^{+0.22}_{-0.17}$
PL	0.4	$13.6^{+3.1}_{-2.4}$	$2.59^{+0.34}_{-0.28}$	411	$0.65^{+0.10}_{-0.09}$
PL+BB(PL)	0.72	$2.84^{+2.66}_{-1.51}$	$1.23 \pm 0.62$	407	$0.37^{+0.12}_{-0.10}$
PL+BB(BB)	0.72	$2.8^{+5.6}_{-1.8}$	$0.17^{+0.03}_{-0.03}$	407	$1.0^{+0.6}_{-0.4}$

NOTE. — The fits are for fixed  $n_{\text{H},22} \equiv n_{\text{H}}/10^{22} \text{ cm}^{-2}$ . The uncertainties are given at 68% confidence level for a single interesting parameter. In each case the fits were done using the C statistics (Cash 1979) and the unbinned source and background spectra, with the total of 1052 channels.

<sup>a</sup>Spectral flux in units of  $10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$  at 1 keV.

<sup>b</sup>Projected area of the emitting region for the BB model, in units of  $10^6 \text{ m}^2$ .

<sup>c</sup>BB temperature in keV.

<sup>d</sup>Unabsorbed PL luminosity in the 0.5–8 keV band, in units of  $10^{32} \text{ ergs s}^{-1}$ .

<sup>e</sup>Bolometric BB luminosity, in units of  $10^{32} \text{ ergs s}^{-1}$ .

tion aperture size. The spectrum fits well by an absorbed PL model (see Table 3) with  $n_{\text{H},22} = 1.2 \pm 0.4$  and  $\Gamma = 1.4 \pm 0.4$ . The unabsorbed flux in 0.5–8 keV is  $F_{\text{Ch1}}^{\text{unabs}} \approx 1.4 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ .

#### 2.2.4. Ch2 spectrum

We extracted 90 events within a  $30''$  radius around the best-fit position of Ch2. Based on the PSF simulation, the extraction region contains  $\sim 85\%$  of the source counts if Ch2 is a point source. The background contributes  $\approx 32$  counts, (i.e.  $\approx 36\%$  of the total number of counts). The measured 0.8–7 keV source flux is  $F_{\text{Ch2}} \approx 9 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ , after correcting for vignetting and finite extraction aperture size (assuming a point source). The thermal plasma (mekal) model fits the Ch2 spectrum best, although fits with absorbed PL and BB models are also acceptable (see Table 3 for details).

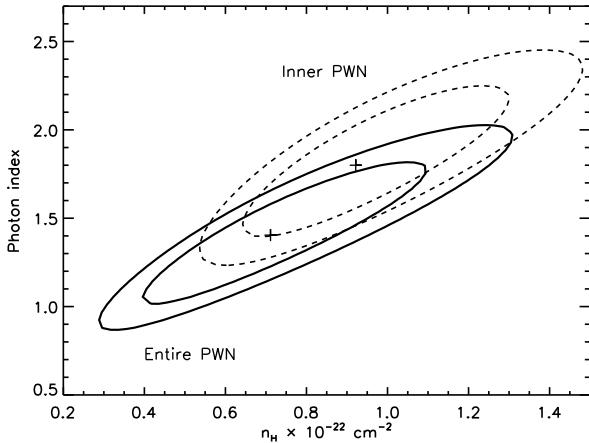


FIG. 4.— Confidence contours (68% and 90%) in the  $n_H$ – $\Gamma$  plane for the PL fit to the inner (dashed) and entire (solid) PWN spectra. The contours are obtained with the PL normalization fitted at each point of the grid.

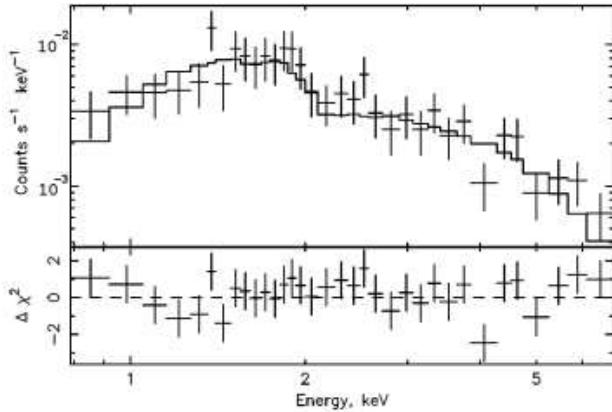


FIG. 5.— Entire (outer+inner) PWN spectrum fitted with the PL model (see Table 1 for details).

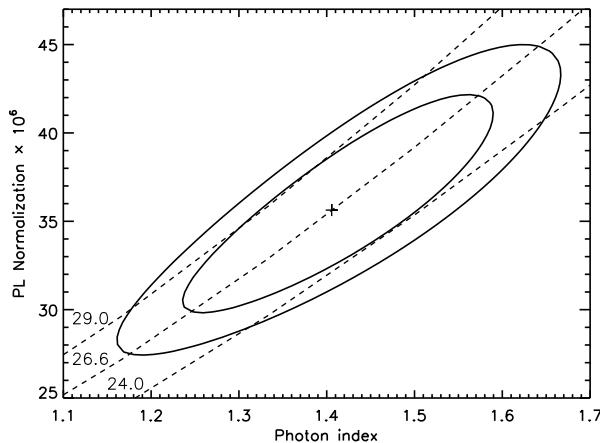


FIG. 6.— Confidence contours (68% and 90%) for the PL fit to the entire PWN spectrum (for a fixed  $n_{H,22} = 0.72$ ). The PL normalization is in units of  $10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$  at 1 keV. The dashed curves are the loci of constant unabsorbed flux in the 0.5–8 keV band; the flux values near the curves are in units of  $10^{-14}$   $\text{ergs} \text{cm}^{-2} \text{s}^{-1}$ .

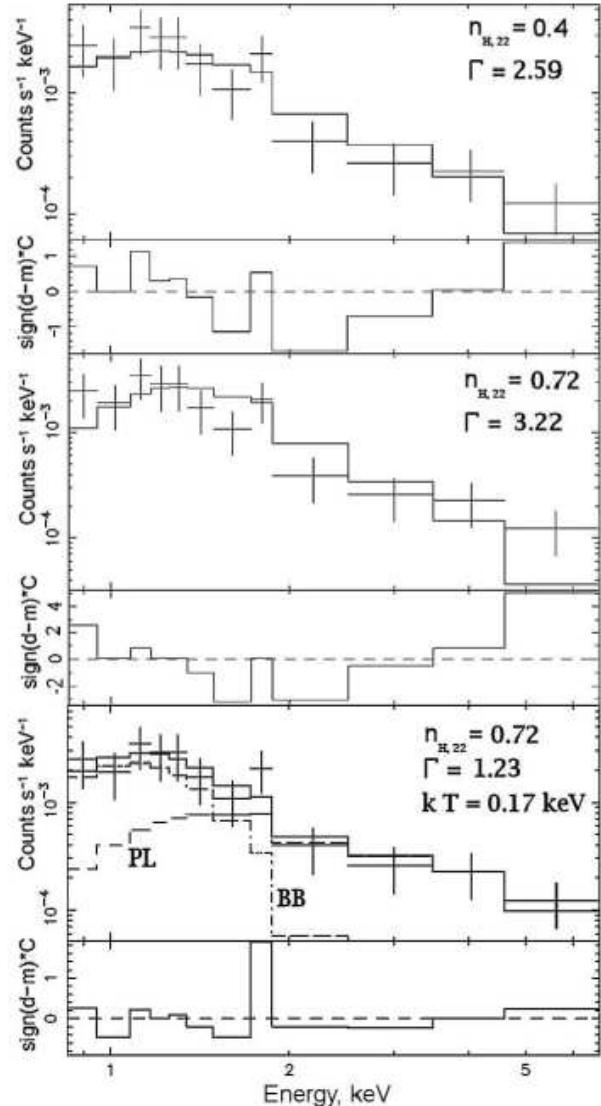


FIG. 7.— *Top*: Pulsar spectrum fitted with the absorbed PL model. *Middle*: Pulsar spectrum fitted with the absorbed PL model where the  $n_H$  was fixed at the best-fit value for the entire PWN ( $n_{H,22} = 0.72$ ). *Bottom*: The pulsar spectrum fitted with the PL+BB model with fixed  $n_{H,22} = 0.72$ . The dashed and dash-dotted histograms correspond to the BB and PL components, respectively. The residual panels show the contributions of the energy bins into the best-fit C-statistic (multiplied by  $-1$  when the number of data counts is smaller than the number of model counts).

### 2.3. Timing

The 3.24 s time-resolution of this observation is insufficient to observe the 82.7 ms pulsations from the pulsar. We found no significant variability in the Ch1 and Ch2 lightcurves.

### 2.4. Archival X-ray data

The region of interest has been previously observed by ASCA for 39 ks (Bamba et al. 2003). The ASCA GIS image in Figure 3c shows a region of enhanced X-ray brightness that encompasses J1809 and its compact PWN; however, the diffuse X-ray emission also extends at least  $\sim 10'$  southward, covering the central region of the brightest part of HESS J1809.

The field was also partly observed by the *XMM-Newton* as a part of the Galactic plane survey (PI: R. Warwick). A point-like object is clearly seen at the pulsar position in the combined EPIC (MOS1+MOS2+PN) image shown in Figure

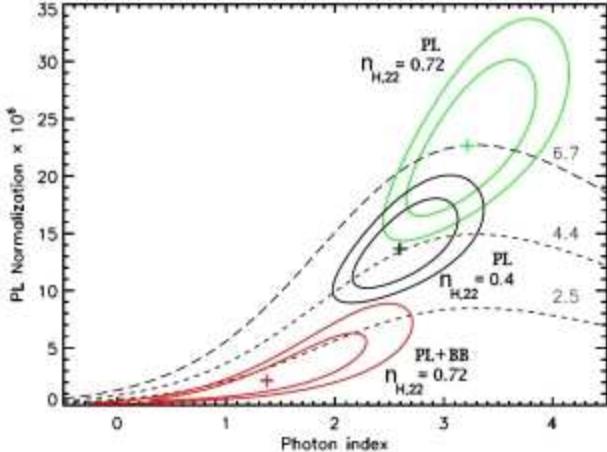


FIG. 8.— Confidence contours (68% and 90%) for the PL fit to the pulsars's spectrum with  $n_{\text{H},22} = 0.72$  (green), PL+BB fit with  $n_{\text{H},22} = 0.72$  (red) and PL fit with  $n_{\text{H},22} = 0.4$  (black) which is the best-fit value for the PL model. The PL normalization is in units of  $10^{-6}$  photons  $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$  at 1 keV. The dashed curves are the lines of constant unabsorbed flux in the 0.5–8 keV band (the flux values are in units of  $10^{-14}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$ ).

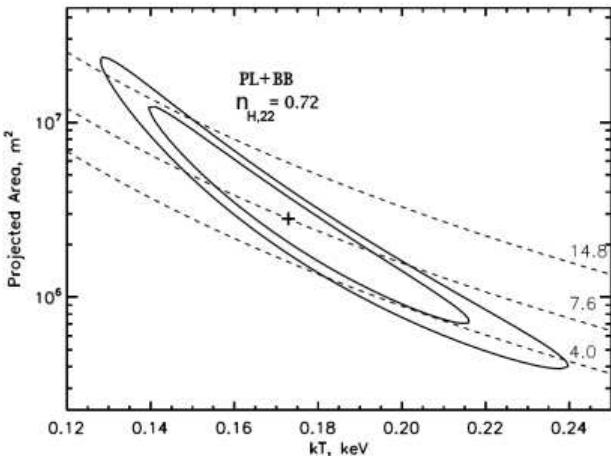


FIG. 9.— Confidence contours (68% and 90%) for the BB component of the BB+PL fit to the pulsar's spectrum, for  $n_{\text{H},22} = 0.72$ . The BB normalization (vertical axis) is the projected emitting area in units of  $\text{m}^2$ , assuming the distance of 3.5 kpc. The lines of constant bolometric flux (in units of  $10^{-14}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$ ), are plotted as dashed lines.

TABLE 3  
FITS TO THE CH1 AND CH2 SPECTRA

Source Model	$n_{\text{H},22}$	$\mathcal{N}^a$ or $\mathcal{A}^b$	$\Gamma$ or $kT^c$	(C or $\chi^2$ ) <sup>d</sup> /dof	$F_{\text{X}}^{\text{up}}$ or $F_{\text{bol}}^{\text{c}}$
Ch1	PL	$1.17^{+0.43}_{-0.39}$	$17.8^{+12.8}_{-7.3}$	$1.42^{+0.40}_{-0.38}$	291/523
Ch2	PL	$0.66(<1.4)$	$\sim 45$	$\sim 6$	$2.3/3$
Ch2	BB	$0.3(<1.1)$	$\sim 0.28d^2_1$	$\approx 0.16$	$2.4/3$
Ch2	mekal	$0.6^{+0.6}_{-0.2}$	$\sim 2.6$	$0.7 \pm 0.2$	$1.1/3$

NOTE. — The uncertainties are given at the 68% confidence level for a single interesting parameter. For Ch2, the upper limits on  $n_{\text{H}}$  value (at 68% confidence) are given in brackets, the lower limits are not constrained at the same confidence level.

<sup>a</sup>Normalization for the PL model is the spectral flux at 1 keV in  $10^{-6}$  photons  $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ . Normalization for the mekal model is the Emission Measure (EM) in  $10^{53} \text{ cm}^{-3}$ , scaled to a distance of 1 kpc.

<sup>b</sup>Projected area of the emitting region for the BB model, in units of  $10^6 \text{ m}^2$ , normalized to  $d = 1 \text{ kpc}$ .

<sup>c</sup>BB temperature in keV.

<sup>d</sup>We use the C statistic for Ch1 and the  $\chi^2$  statistic for Ch2.

<sup>e</sup>Unabsorbed PL flux in the 0.5–8 keV band or bolometric BB flux, in units of  $10^{-13}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$  (corrected for vignetting and finite extraction aperture size).

3. However, the short 8 ks exposure, the off-axis location, and the high EPIC background do not allow one to detect the faint extended component, while the compact PWN cannot be resolved from the pulsar because of the broad PSF of *XMM-Newton*.

### 2.5. Optical-IR-radio data

To understand the nature of the X-ray sources Ch1 and Ch2, projected within the HESS source image and look for other sources that could be related to the TeV emission, we have examined the field at other wavelengths. We found no counterparts to Ch1 in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) or Digital Sky Survey (DSS2)<sup>5</sup> catalogs, up to the limiting magnitudes  $K_s = 15.4$ ,  $H = 16$ ,  $J = 17.5$ ,  $R = 19$ , and  $B = 21$ . The nearest optical/NIR source is a 2MASS point source ( $J = 15.45 \pm 0.05$ ,  $H = 13.10 \pm 0.05$ ,  $K = 12.06 \pm 0.04$ ) located at R.A. =  $18^{\text{h}}09^{\text{m}}40.92^{\text{s}}$ , decl. =  $-19^{\circ}25'45.7''$ . The  $3.2''$  offset from the best-fit Ch1 position substantially exceeds the position uncertainty of  $\approx 0.4''$ . Figure 3 shows that Ch1 is projected very close to the extended Source A seen in the radio and IR images.

The only NIR/optical source within the  $5''$  radius of the Ch2 position is a star, NOMAD1 0705–0568334 in the NOMAD catalog (Zacharias et al. 2005), offset by only  $0.9''$  from Ch2. Given the relatively large uncertainty of the Ch2 position (see §2.1), the positions of the star and Ch2 can be considered coincident. The X-ray-to-optical flux ratio,  $F_X/F_V \sim 2 \times 10^{-3}$ , is typical for a K star with coronal X-ray emission (Maccacaro et al. 1988). The soft X-ray spectrum of Ch2 and the optical-NIR magnitudes of the star ( $B = 14.96$ ,  $V = 14.66$ ,  $R = 14.19$ ,  $J = 13.35$ ,  $H = 12.84$ , and  $K = 12.72$ ) support such an interpretation. No Ch2 counterpart is seen in the NVSS 20 cm image or in the *Spitzer* 8 and 24  $\mu\text{m}$  images.

The NVSS 20 cm image ( $45''$  restoring beam size) and the  $25''$  resolution images by Brogan et al. (2004) show two bright compact radio sources (marked A and B in Fig. 3) projected near the HESS source center, with the 1.4 GHz spectral fluxes of 0.3 Jy and 0.15 Jy for Source A and Source B, respectively. Within these sources, 6.7 GHz methanol masers have been detected (Pestalozzi et al. 2005): G10.95+0.02 in Source A (peak flux 15 Jy at 6.7 GHz,  $V_{\text{LSR}} = 24 \pm 1 \text{ km s}^{-1}$ , near-distance 3.2 kpc) and G11.03+0.06 in Source B (peak flux 0.7 Jy at 6.7 GHz,  $V_{\text{LSR}} = 20 \pm 1 \text{ km s}^{-1}$ , near-distance 2.9 kpc).

Both A and B are also very bright far-IR sources, IRAS 18067–1927 and IRAS 18067–1921 in the IRAS Point Source Catalog v2.1 (IPAC Infrared Science Archive<sup>6</sup>), with peak fluxes of 1292 and 513 Jy at 60  $\mu\text{m}$ , respectively. The *Spitzer* IRAC 8  $\mu\text{m}$  and MIPS 24  $\mu\text{m}$  images (Fig. 3g, h; taken from the GLIMPSE survey<sup>7</sup>) show extended sources of irregular shape at these positions, with characteristic sizes of  $\sim 1'$ . They are not seen in the DSS and 2MASS images, which suggests that they are intrinsically very cold ( $T \sim 70 \text{ K}$ ) and/or strongly absorbed molecular/dust complexes.

The *Spitzer* images also reveal an extended source with an interesting morphology (shell-like in the 24  $\mu\text{m}$  image), located  $\sim 10'$  southwest of the HESS J1809 center (see Fig. 3g, h). The source has an extended radio counterpart (NVSS 180919–192904) clearly seen in the 20 cm image shown in the same figure. It has been detected by Helfand et al. (2006) in the Multi-Array Galactic Plane Survey (MAG-

<sup>5</sup> see <http://archive.eso.org/dss/dss>

<sup>6</sup> <http://irsa.ipac.caltech.edu/>

<sup>7</sup> <http://www.astro.wisc.edu/sirf/>

PIS) and proposed to be an SNR candidate G10.8750+0.0875. It is possible that this extended source contributes to the non-uniform X-ray background on the S1 chip (see §2.1 and Fig. 3b). The SNR candidates G11.03–0.05 and G11.18+0.11 (Brogan et al. 2004; see Fig. 3b) are too faint to be seen in the shallow NVSS images.

### 3. DISCUSSION.

The sub-arcsecond angular resolution of *Chandra* has allowed us to resolve the compact J1809 PWN, disentangle the pulsar and the extended emission components, and measure their properties separately. Thanks to the very low ACIS background, we were also able to detect the faint large-scale emission surrounding the compact PWN. The observation has also provided serendipitous coverage of the central part of the extended TeV source HESS J1809 and revealed two X-ray sources bright enough to permit spectral measurements and accurate determination of their positions. In this section we discuss some implementations of our findings.

#### 3.1. The J1809 PWN

##### 3.1.1. Luminosity and spectrum

At the plausible distance of 3.5 kpc, the unabsorbed X-ray luminosity of the compact PWN,  $L_{\text{pwn}} \sim 4 \times 10^{32} \text{ ergs s}^{-1}$ , corresponds to the X-ray efficiency,  $\eta_{\text{pwn}} \equiv L_{\text{pwn}}/\dot{E} \sim 2.2 \times 10^{-4}$ , similar to those of PWNe around younger and more powerful Vela-like pulsars (see Fig. 10). Some of the detected X-ray PWNe associated with older and less powerful pulsars have similar or higher X-ray efficiencies (e.g.,  $\eta_{\text{pwn}} \sim 2 \times 10^{-3}$  and  $4 \times 10^{-4}$  for J1509–5850 [ $\tau = 150$  kyr] and B0355+54 [ $\tau = 560$  kyr], respectively; Kargaltsev et al., in preparation), while others show much lower efficiencies (e.g.,  $\eta_{\text{pwn}} \sim 5 \times 10^{-5}$  and  $7 \times 10^{-6}$  for PRS J1740+1000 [ $\tau = 100$  kyr] and Geminga [ $\tau = 340$  kyr], respectively; Kargaltsev et al., in preparation; Pavlov et al. 2006). This indicates that  $\eta_{\text{pwn}}$  is not significantly correlated with  $\tau$  or  $\dot{E}$ , at least for young and middle-aged pulsars ( $\tau \lesssim 1$  Myr), perhaps because, in addition to  $\dot{E}$  and  $\tau$ , it depends on other factors (e.g., the pulsar’s speed and the angle between the spin and magnetic axes).

The spectral slope of the J1809 PWN,  $\Gamma_{\text{pwn}} = 1.4 \pm 0.1$ , is similar to those of the PWNe around Vela-like pulsars (listed in Table 2 of Kargaltsev et al. 2007a, hereafter KPG07a), except for two bow-shock PWNe with prominent tails, J1747–2958 (the Mouse; Gaensler et al. 2004) and B1757–24 (the Duck; Kaspi et al. 2001), which show softer spectra ( $\Gamma = 2.0 \pm 0.2$  and  $2.5 \pm 0.3$ , respectively). Comparing the J1809 spectrum with those of older PWNe, we see that it is similar to the spectra of relatively compact PWNe (e.g.,  $\Gamma = 1.4 \pm 0.3$  for the bright part of the B0355+54 PWN; McGowan et al. 2006), but it is harder than the spectra of the extended tails in J1740+1000 and J1509–5850 PWNe ( $\Gamma = 1.8 \pm 0.4$  and  $2.2 \pm 0.3$ , respectively; Kargaltsev et al., in preparation). It hints that PWN spectra are correlated with PWN morphology rather than with the pulsar age and spindown power.

##### 3.1.2. PWN morphology

The unknown proper motion of J1809 and the faintness of the surrounding large-scale emission complicate the interpretation of the observed PWN, but its “cometary” appearance strongly suggests that the pulsar’s motion plays a major role.

**3.1.2.1. Bow shock in a nearly isotropic pulsar wind?** — The compact J1809 PWN is elongated approximately along

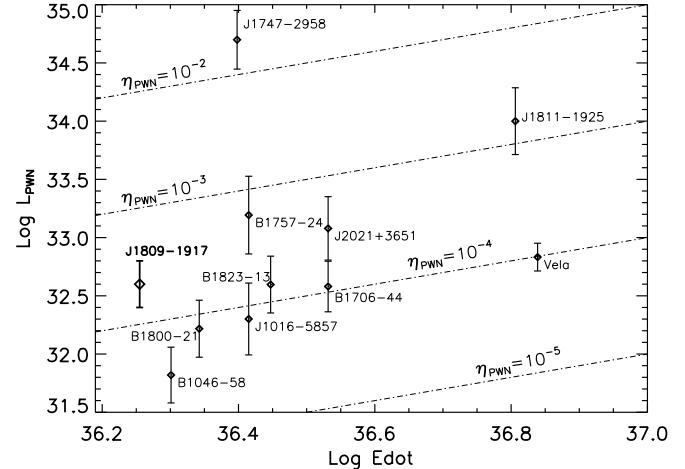


FIG. 10.— PWN luminosity versus pulsar spin-down power showing J1809 and 10 Vela-like pulsars observed with *Chandra*. The luminosities are estimated for the 0.5–8 keV band. The dash-dot lines are the lines of constant PWN efficiency,  $\eta_{\text{pwn}}$ . The error bars include the statistical uncertainties and the nominal 30% distance uncertainties, except for the Vela pulsar whose parallax has been measured (Dodson et al. 2003a).

the north-south direction, with the pulsar located much closer to its southern end (see Fig. 1). Such a cometary morphology can be attributed to a bow shock created by the pulsar moving supersonically in the southern direction (P.A.  $\approx 194^\circ$ ). The apex of the termination shock (TS) of the pulsar wind is located at the distance

$$R_h \approx \left[ \frac{\dot{E} f_\Omega}{4\pi c(p_{\text{amb}} + p_{\text{ram}})} \right]^{1/2} \quad (1)$$

ahead of the pulsar. At this distance, the pulsar wind pressure,  $p_w = \dot{E} f_\Omega (4\pi c r_s^3)^{-1}$  ( $f_\Omega$  takes into account anisotropy of the pulsar wind), is balanced by the sum of the ambient pressure,  $p_{\text{amb}} = \rho k T (\mu m_H)^{-1} = 1.38 \times 10^{-12} n \mu^{-1} T_4 \text{ ergs cm}^{-3}$ , and the ram pressure,  $p_{\text{ram}} = \rho v^2 = 1.67 \times 10^{-10} n v_7^2 \text{ ergs cm}^{-3}$  ( $T_4 = T/10^4 \text{ K}$ ,  $v_7 = v/10^7 \text{ cm s}^{-1}$ ,  $\mu$  is the molecular weight, and  $n = \rho/m_H$  is in units of  $\text{cm}^{-3}$ ). Assuming  $p_{\text{ram}} \gg p_{\text{amb}}$  (or  $\mathcal{M} \gg 1$ , where  $\mathcal{M} = v/c_s$  is the Mach number,  $c_s = (5kT/3\mu m_H)^{1/2} = 12\mu^{1/2} T_4^{1/2} \text{ km s}^{-1}$  is the sound speed in the ambient medium), we obtain  $R_h = 1.7 \times 10^{17} n^{-1/2} f_\Omega^{1/2} v_7^{-1} \text{ cm}$ .

The shocked pulsar wind, observed in X-rays as a bow-shock PWN, is confined between the TS and the contact discontinuity (CD) surface. For  $\mathcal{M} \gg 1$  and a *nearly isotropic* preshock wind with a low magnetization parameter  $\sigma$ , the TS acquires a bullet-like shape (Bucciantini et al. 2005, hereafter B05). The distance  $R_h$  between the pulsar and the bullet head is given by equation (1), while the CD surface head is at a distance  $\approx 1.3R_h$  from the pulsar. Assuming that the sharp rise in the brightness profile (Fig. 2) at about  $3''$  from the pulsar (i.e.  $1.6 \times 10^{17} d_{3.5} \text{ cm}$  in the plane of the sky) corresponds to the CD head, we can estimate the pulsar velocity,

$$v \sim 140 n^{-1/2} d_{3.5}^{-1} f_\Omega^{1/2} \sin i \text{ km s}^{-1}, \quad (2)$$

and the Mach number,  $\mathcal{M} \sim 12n^{-1/2} T_4^{-1/2} \mu^{1/2} f_\Omega^{1/2} d_{3.5}^{-1} \sin i$ , where  $i$  is the angle between the velocity vector and the line of sight.

The observed projected length,  $\sim 12''$ , and width,  $\sim 3''$ , of the inner PWN are close to the length  $\sim 7R_h \sim 15''$ , and width,

$\sim R_h \sim 2''$ , of the TS bullet, predicted by the B05 models for  $\sigma \sim$  a few  $\times 10^{-3}$ . The width of the outer PWN,  $\sim 20''$ , can be interpreted as the diameter of the CD shell (approximately cylindrical behind the pulsar, with a diameter  $\sim 8R_h \sim 18''$ , according to B05).

The B05 models also predict a tail behind the back surface of the TS bullet, where the collimated shocked pulsar wind flows with subrelativistic velocities:  $0.1c$ – $0.3c$  in the inner channel with a cylindrical radius  $\sim R_h$  ( $\sim 2''$  in our case), and up to  $0.8c$ – $0.9c$  in the outer channel, confined between the cylindrical surfaces with radii  $\sim R_h$  and  $\sim 4R_h$ . The lack of an extended tail in the ACIS images is puzzling; it could be due to a relatively low Mach number of the pulsar and insufficient sensitivity of the short ACIS exposure. On the other hand, the shape of the faint thin feature northeast of inner PWN hints that it may be a bent extension of the inner PWN, which is difficult to explain if this is a strongly collimated, mildly relativistic flow just behind the back surface of the TS bullet (unless the flow is subject to kink instabilities). However, statistical significance of this feature is too low to draw any definitive conclusions.

**3.1.2.2. Effects of pulsar wind anisotropy.** — We should note that the B05 models assume an isotropic pulsar wind ( $f_\Omega = 1$ ). We know from observations of young pulsars, such as Crab and Vela, that the wind is not isotropic, but it is mostly confined to the equatorial plane. In addition, in young PWNe we often see jets along the pulsar's spin axis. These jets can be formed by polar outflows originating in the pulsar magnetosphere or they can be created by tangential inflows just outside the equatorial TS surface converging toward the spin axis (Komissarov & Lyubarsky 2004). We are unaware of PWN models that include both the pulsar wind anisotropy and the ram pressure effects. We can, however, expect that, in the case of an anisotropic wind, the PWN morphology, at least close to the pulsar, would depend on the orientation of the spin axis with respect to the pulsar's velocity.

As *Chandra* observations have shown, the spin axis is oriented along the direction of pulsar's motion in a number of young pulsars (e.g., Ng & Romani 2004). In this case, we expect that the equatorial outflow would form a shell between the TS and the CD surface behind the pulsar, filled by a relativistic plasma with a subrelativistic bulk flow velocity. The morphology of the X-ray emission from such a PWN would be generally similar to that in the case of isotropic wind, although we may expect to see a shell-like (rather than filled) PWN appearance at sufficiently high resolution. Such a structure ("outer tails") is possibly seen in the Geminga PWN (Caraveo et al. 2003; Pavlov et al. 2006). As for the jets coaligned with the pulsar velocity vector, the rear jet is expected to be seen along the axis of the shell filled by the shocked equatorial wind behind the pulsar (at least if the jet originates from the pulsar magnetosphere), as observed in the Geminga PWN (Pavlov et al. 2006). The front jet is expected to pierce the head of the shell (as  $f_\Omega \gg 1$  in the jet), and it can be seen ahead of the pulsar unless it is crushed by the ram pressure. The jets could be of quite different brightness and length because of the Doppler boosting and different effective pressures in front and behind the pulsar.

In the case of J1809, the high-resolution images shown in Figure 1 indicate the presence of a narrow structure (with a linear extent of  $\simeq 3''$ ) just south of the pulsar, which might be interpreted as a front jet. Furthermore, the heavily binned low-resolution image (Fig. 3b) shows a faint structure extend-

ing in the direction of the presumed pulsar's proper motion. Although tentative, the structure is consistent with the X-ray morphology seen in the ASCA GIS image (Fig. 3c). Therefore, one could speculate that these structures are connected to each other and could be parts of the front jet. In this interpretation, the rear jet may contribute to the inner PWN emission, and the above-mentioned bent extension of the inner PWN (§3.1.2.1) could represent the outer part of the rear jet. Although barely supported by the existing data, the jet hypothesis offers a way to explain the offset large-scale X-ray (and TeV) emission south of the pulsar, which cannot be associated with the shocked pulsar wind under the assumption of wind isotropy. We speculate that this emission could be produced by particles supplied through the front jet (similar to the Vela PWN; Pavlov et al. 2003; Kargaltsev & Pavlov 2004). However, to account for the luminous TeV emission ( $L_\gamma \sim 2 \times 10^{-2} d_{3.5}^2 \dot{E}$ ), the front jet would have to carry a substantial fraction of the pulsar's spindown power, unlike the northwest jet of the Vela PWN whose energy injection rate is only  $\sim 10^{-3} \dot{E}$ .

We cannot also exclude a possibility that the spin axis of the J1809 pulsar, and hence the PWN jets, are substantially misaligned with the direction of pulsar motion. For instance, one could assume that the jets are nearly perpendicular to the velocity vector (i.e. this vector lies in the equatorial plane; a possible example is PSR B1706–44 and its PWN; Romani et al. 2005). In this case, the jets would be bent backwards (or even destroyed) by the ram pressure of the oncoming ambient medium, while the TS in the equatorial outflow (ring-like without ram pressure applied) would turn into an ellipse-like structure elongated in the direction of pulsar motion, with the pulsar displaced along the major axis toward the TS head. The observational appearance of the shocked pulsar wind would then depend on the inclination of the orbital plane to the line of sight, but at most inclinations we would see an elongated structure with the pulsar shifted from the center of the PWN in the direction of the velocity vector, in a qualitative agreement with the observed shape of the inner PWN. Of course, such an interpretation would imply a higher pulsar velocity than that estimated above for a nearly isotropic pulsar wind (see eq. [2]). On the other hand, in such a geometry the wind could propagate to larger distances ahead of the pulsar because the CD could be easier destroyed by various instabilities, and the pulsar wind would be mixed with the shocked ambient medium. We note, however, that this picture can hardly explain the large-scale X-ray emission south-southwest of the pulsar, which, in this case, could be attributed to the host SNR or the crushed relic PWN (see §3.3 and §3.4.2, respectively).

Overall, we can conclude that the observed PWN morphology is generally consistent with the assumption of the supersonic pulsar motion, which implies a low ambient pressure (e.g.,  $p_{\text{amb}} \ll 2 \times 10^{-10} f_\Omega d_{3.5}^{-2} \sin^2 i$  ergs cm $^{-3}$  for a nearly isotropic pulsar wind). On the other hand, modeling of magnetized anisotropic winds from fast-moving pulsars, deeper X-ray observations, and proper motion measurements are needed to firmly establish the nature of the J1809 PWN and infer its properties quantitatively.

### 3.2. The pulsar

The spectrum of the J1809 pulsar is less certain than that of the PWN. Although the one-component PL model formally fits the spectrum, the fit yields a rather large  $\Gamma \simeq 2.6$ – $3.2$  and suggests a smaller  $n_H$  than the one obtained from the

PL fit to a better quality PWN spectrum. An alternative description of the pulsar spectrum is provided by the two-component PL+BB model that is often used to fit the spectra of young and middle-aged pulsars (see, e.g., KPG07a and references therein). The PL component of the PL+BB fit gives  $\Gamma_{\text{psr}} \simeq 1.2 \pm 0.6$ , similar to  $\Gamma_{\text{pwn}}$  and to the spectral slopes of other pulsars of similar ages (see e.g., KPG07a). In any case, the slope is much softer than  $\Gamma_{\text{psr}} = 2.1 - 2.9 \dot{E}_{36}^{-1/2} \approx 0.1$  predicted by the Gotthelf's (2003) correlation. The X-ray efficiency of the pulsar,  $\eta_{\text{psr}} \equiv L_{\text{psr}}/\dot{E} \sim 2 \times 10^{-5} d_{3.5}^2$  in the 0.5–8 keV band, is also not unusual for Vela-like pulsars, as well as the ratio  $L_{\text{pwn}}/L_{\text{psr}} \sim 10$  (see KPG07a).

The possible thermal component of the PL+BB fit is poorly constrained, not only because of the scarce statistics but also because the soft thermal radiation is strongly absorbed by the ISM. The BB temperature,  $T \sim 1.7\text{--}2.3$  MK, emitting area  $\mathcal{A} \sim 10^6\text{--}10^7$  m<sup>2</sup>, and bolometric luminosity,  $L_{\text{psr}}^{\text{bol}} \sim (0.6\text{--}1.6) \times 10^{32}$  ergs s<sup>-1</sup>, are similar to those found from the PL+BB fits for Vela-like pulsars. The temperature is a factor of two higher than the NS surface temperatures predicted by standard NS cooling models for the 50 kyr age (e.g., Yakovlev & Pethick 2004), and the corresponding emitting area is smaller than the NS surface area. However, the actual spectrum of the NS thermal radiation can differ substantially from the BB model. In particular, fitting the spectra with hydrogen atmosphere models (Pavlov et al. 1995) yields lower effective temperatures and larger emitting areas (see Pavlov et al. 2001a for the specific example of the Vela pulsar). Unfortunately, the quality of the data does not warrant fits with more complicated atmosphere models. Unlike the temperature and the area, the bolometric luminosity is not so sensitive to the presence and properties of the NS atmosphere. The comparison with the NS cooling models shows that the J1809's bolometric luminosity is a factor of  $\sim 10$  lower than predicted by the “basic” theoretical cooling curve ( $M_{\text{NS}} = 1.3M_{\odot}$ , no superfluidity); it is consistent with the cooling curves for heavier NSs (e.g.,  $M_{\text{NS}} = 1.5\text{--}1.6M_{\odot}$ ) for various superfluidity models (Yakovlev & Pethick 2004).

### 3.3. Host SNR

With the velocity given by Equation (2), the pulsar would have traveled a distance of  $\sim 7n^{-1/2}d_{3.5}^{-1}f_{\Omega}^{1/2} \sin i$  pc during the time equal to its spindown age,  $\tau = 51$  kyr. This corresponds to a displacement of  $\sim 7'n^{-1/2}d_{3.5}^{-2}f_{\Omega}^{1/2} \sin^2 i$  in the plane of the sky and, for  $n^{-1/2}d_{3.5}^{-2}f_{\Omega}^{1/2} \sin^2 i \sim 0.6$ , places the sky projection of the pulsar's birthplace close to the apparent center of the radio SNR G11.18+0.11 (see Fig. 3b), suggesting that J1809 and G11.18+0.11 were created by the same supernova explosion. This conjecture implies that the pulsar has overtaken the SNR shell and left the high-pressure SNR interiors, which is consistent with the assumption  $p_{\text{amb}} \ll p_{\text{ram}}$ , used to obtain the pulsar velocity estimate. This could explain why J1809 looks so different from those Vela-like PWNe that do not show cometary morphology because they are moving subsonically in high-pressure SNR interiors (see KPG07a for examples). However, if G11.18+0.11 is at  $d \approx 3.5$  kpc (the presumed distance to J1809), then its size,  $D \approx 8d_{3.5}$  pc, would be surprisingly small for a 50 kyr old SNR, unless it is expanding in an unusually dense environment. To get more consistent SNR age and size, we have to assume a larger distance and a smaller pulsar's true age, which would require a lower ambient density around J1809 to match the pulsar's birth-

place with the center of G11.18+0.11, resulting in a higher inferred pulsar velocity and Mach number. For instance, if we assume  $d = 5$  kpc (i.e.,  $D \sim 11$  pc) and the true age = 20 kyr, then  $n \sim 0.1f_{\Omega} \sin^4 i$  cm<sup>-3</sup> is required, which corresponds to  $v \sim 300(\sin i)^{-1}$  km s<sup>-1</sup>,  $\mathcal{M} \sim 25T_4^{-1/2}\mu^{1/2}(\sin i)^{-1}$ . Thus, given the uncertainty of the pulsar's true age and distance, we cannot rule out the possibility that G11.18+0.01 is the host SNR for J1809.

It is also possible that G11.18+0.01 is just a background SNR accidentally projected near the pulsar. In this case, the real host SNR might be associated with the extended emission around J1809 seen in the *Chandra* and *ASCA* images (Fig. 1, *bottom right* and Fig. 3c). The faintness of the large-scale X-ray emission does not allow one to determine its origin (thermal or nonthermal) and, therefore, thermal plasma emission from the SNR interior cannot be excluded until better quality data are obtained (see §2.2.1). However, the size of this putative SNR is too small, and, more importantly, the observed PWN morphology does not look consistent with this hypothesis. Therefore, it seems more plausible that the extended emission is synchrotron radiation related to the PWN (see §3.1.2.2) rather than thermal emission from hot gas in SNR interior. Measuring the X-ray spectrum of the extended emission in a deeper observation would distinguish between these possibilities.

One could also speculate that the host SNR is not seen because its size is larger than the field-of-view of our observation ( $\gtrsim 20$  pc at  $d = 3.5$  kpc), and the SNR interior has become cold enough ( $T \lesssim 10^5$  K) to provide  $\mathcal{M} \gg 1$  and be undetectable in X-rays. This option remains quite viable if the pulsar's true age is close to (or exceeds) its spindown age.

### 3.4. Origin of HESS J1809

TeV radiation can be produced by the inverse Compton scattering (ICS) of low-frequency radiation (e.g., the cosmic microwave background radiation [CMBR]) off relativistic electrons. Alternatively, it can be generated by the  $\pi^0 \rightarrow \gamma + \gamma$  decay, the  $\pi^0$  mesons being produced when relativistic protons interact with the ambient matter. Therefore, to understand the nature of a TeV source, one should identify the *source* of relativistic particles and the *target* with which these particles interact.

#### 3.4.1. Possible targets where the TeV radiation is produced

The omnipresent target for relativistic electrons producing TeV photons by the ICS is the CMBR, with the energy density  $U_{\text{CMBR}} = 0.26 \text{ eV cm}^{-3}$ . To produce TeV photons with energy  $E_{\gamma}$  by upscattering the CMBR photons with energy  $\epsilon \sim 3kT \sim 4 \times 10^{-4}$  eV, electrons with the Lorentz factor  $\gamma \sim 5 \times 10^7 E_{\text{TeV}}^{1/2}$  [i.e.  $E_{\gamma} \sim 25E_{\text{TeV}}^{1/2}$  TeV] are required, where  $E_{\text{TeV}} = E_{\gamma}/(1 \text{ TeV})$ . As  $\gamma\epsilon \sim 20\text{--}100 \text{ keV} \ll m_e c^2$  for  $E_{\gamma} \sim 1\text{--}20$  TeV, the ICS occurs in the Thompson regime. The same relativistic electrons produce synchrotron photons with energy

$$E_{\text{syn}} \sim \gamma^2 h\nu_{\text{cyc}} \sim 5\gamma_7^2 B_{-5} \text{ eV} \sim 0.1 \frac{E_{\text{TeV}} B_{-5}}{\epsilon/(4 \times 10^{-4} \text{ eV})} \text{ keV}, \quad (3)$$

where  $\gamma_7 = \gamma/10^7$  and  $B_{-5} = B/(10 \mu\text{G})$ .

Close to the Galactic plane, where HESS J1809 is situated, a factor of a few higher radiation energy density can be provided by IR emission from interstellar dust and Galactic starlight. For instance, the models of interstellar radiation

field by Strong et al. (2000) give the energy densities of 0.6 and 2.7 eV cm<sup>-3</sup> for these two components, respectively, at the galactocentric distance of  $\sim 4$  kpc. Since the ICS proceeds in the Klein-Nishina (K.-N.) regime for  $\epsilon \gtrsim 1E_{\text{TeV}}^{-1}$  eV (i.e., the K.-N. effects become important at  $\epsilon \gtrsim$  a few  $\times 10^{-2}$  eV for the high-energy end of the TeV photon spectrum), we should use a more general formula for estimating the electron Lorentz factor:

$$\gamma \sim 10^6 \left[ E_{\text{TeV}} + (E_{\text{TeV}}^2 + E_{\text{TeV}}/\epsilon_{\text{eV}})^{1/2} \right], \quad (4)$$

where  $\epsilon_{\text{eV}} = \epsilon/(1\text{eV})$ . The electrons with such a Lorentz factor generate synchrotron photons with energy  $E_{\text{syn}} \sim 0.05 \left[ E_{\text{TeV}} + (E_{\text{TeV}}^2 + E_{\text{TeV}}/\epsilon_{\text{eV}})^{1/2} \right]^2 B_{-5}$  eV. For instance, electrons with  $\gamma \sim 2 \times 10^7$  (i.e.  $E_e \sim 40$  TeV) produce photons with  $E_\gamma = 10$  TeV by upscattering background starlight photons with a typical energy  $\epsilon \sim 1$  eV, and the same electrons produce synchrotron radiation in a far-UV range,  $E_{\text{syn}} \sim 6$  eV, in an interstellar field of  $3 \mu\text{G}$ . Although the radiation energy density of the starlight can substantially exceed that of the CMBR, the emissivity is reduced by the smaller Compton cross section in the K.-N. regime and smaller photon number density.

The radiation energy density and photon number density (hence TeV emissivity) can be enhanced in the vicinity of very bright sources. The radiation energy density at an angular distance  $\theta$  from a source of radiation can be estimated as  $U = F/(c\theta^2)$ , where  $F$  is the source energy flux observed at Earth; it exceeds the ambient radiation energy density,  $U_{\text{amb}}$ , at

$$\theta > (F/cU_{\text{amb}})^{1/2}. \quad (5)$$

The multiwavelength data show two very bright radio-IR objects near the center of HESS J1809 – Source A and Source B (see Fig. 3), which are likely molecular-dust complexes in star-forming regions. An approximate integration of the spectral flux of Source A gives its total flux  $F_A \sim 10^{-7}$  ergs cm<sup>-2</sup> s<sup>-1</sup> (i.e. the luminosity  $L_A \sim 1.5 \times 10^{38} d_{3.5}^2$  ergs s<sup>-1</sup>). This means that the radiation energy density near this source exceeds  $U_{\text{amb}}$  at  $\theta < 5'(U_{\text{amb}}/1\text{eV cm}^{-3})^{-1/2}$ . For instance, if the TeV emission is produced by the ICS of IR photons with energies around  $\epsilon \sim 0.02$  eV (which corresponds to the maximum spectral flux of Source A), and  $U_{\text{amb}} \sim 0.1$  eV cm<sup>-3</sup> in this energy range, then  $U > U_{\text{amb}}$  at  $\theta \lesssim 15'$ . This value is close to the observed radius of HESS J1809, which suggests that the sphere of  $\sim 10$  pc of the enhanced radiation field around Source A might be the target where the TeV emission is produced by the ICS off the relativistic electrons supplied by a nearby source [Lorentz factors  $\gamma \sim (0.5-6) \times 10^7$  are required to upscatter the IR photons to  $E_\gamma = 0.5-20$  TeV]. Similar estimates hold for Source B, whose flux is a factor of 2.5 lower, and the size  $\theta$  is a factor of 1.6 smaller, than those for Source A. The hypothesis that the “photon sphere” of Source A or Source B is the site where the TeV emission is produced via ICS could be verified by detection of the accompanying synchrotron radiation. However, most of the energy range of the corresponding synchrotron emission,  $E_{\text{syn}} \sim (1-200)B_{-5}$  eV, is subject to the strong interstellar absorption.

In principle, the TeV emission could be initiated by high-energy nucleons supplied by some source (e.g., a pulsar), which produce decaying  $\pi^0$  mesons in collisions with nucleons of the ambient medium (e.g., Horns et al. 2006). The target in this case would be the nucleonic component of the circumpulsar medium, and we should expect enhanced TeV

emission in dense, cold clouds, if there are such clouds close to the source of high-energy nucleons. The lack of an extended IR or radio counterpart of a size similar to that of HESS J1809 (which would indicate the presence of a large molecular cloud) suggests that the TeV source is not associated with a localized target for high-energy nucleons.

### 3.4.2. Possible sources of relativistic particles

In the case of HESS J1809, the natural source of relativistic electrons (and possibly protons) is the J1809 pulsar. In addition to that, there are the Ch1 and Ch2 X-ray sources and the radio SNR G11.03-0.05, all projected close to the center of HESS J1809 (see Fig. 3). Finally, relativistic particles might be produced by acceleration mechanisms in the forward shock of the putative host SNR of the J1809 pulsar.

The soft X-ray spectrum of Ch2 and the positional coincidence with a field star suggest that the X-ray emission comes from an active stellar corona. Therefore, we conclude that Ch2 is not related to HESS J1809.

If the shell-like radio SNR G11.03-0.05 were a powerful source of relativistic electrons, its synchrotron radiation would have been seen in the X-ray range. Since no X-rays at the SNR location are detected in our *Chandra* observation, this SNR is not a viable candidate for the source of relativistic particles that powers HESS J1809.

As we have discussed in §3.1.2 and §3.3, the faint, large-scale X-ray emission south of the J1809 pulsar is likely not the host SNR of this pulsar, but it is rather related to the J1809 PWN. Moreover, TeV  $\gamma$ -ray emission from an SNR shock is usually associated with the SNR shell, not the interior. Current radio, X-ray and  $\gamma$ -ray data provide no evidence of such a shell around J1809. Therefore, even if the large-scale X-ray emission belongs to the host SNR, HESS J1809 is unlikely to be powered by particles accelerated in the forward shock of this SNR.

Among the X-ray sources detected with *Chandra*, Ch1 is the closest to the projected HESS J1809 center (Fig. 3). The lack of an IR-optical counterpart and the large lower limit on the X-ray-to-optical flux ratio,  $F_X/F_{\text{opt}} \gtrsim 3$ , mean that the X-ray emission from Ch1 comes not from a usual field star. On the other hand, the absorbing hydrogen column density,  $n_{\text{H},22} = 1.2 \pm 0.4$ , is close to that of the J1809 PWN, which suggests that Ch1 is a Galactic object, not an AGN observed through the Galactic plane. The slope of the Ch1 spectrum,  $\Gamma = 1.4 \pm 0.4$ , suggests that it may be either an X-ray binary or a remote PWN unresolved because of the far off-axis location. With the optical extinction estimated from the measured  $n_{\text{H}}$  value (e.g.,  $A_V \sim 4-9$ ), the limits on the optical-NIR magnitudes (see §2.5) virtually exclude a high mass X-ray binary. Although a low mass X-ray binary (LMXB) in a quiescent state could have an X-ray luminosity comparable to that of Ch1,  $L_{\text{Ch1}} \sim 3 \times 10^{32} (d/4 \text{ kpc})^2$  ergs s<sup>-1</sup>, LMXBs are not known to be sources of TeV emission. If Ch1 is a young pulsar with a PWN, then it might provide relativistic particles needed for generating the TeV emission. (We should note, however, that the TeV-to-X-ray flux ratio,  $\sim 150$ , would be much higher than the values,  $\sim 0.01-3$ , inferred for most of the other TeV PWNe, except for the B1800-21, for which the ratio is about 100; see Table 2 in Kargaltsev et al. 2007b, hereafter KPG07b, and references therein). To assess the likelihood of Ch1 being the source of relativistic particles for HESS J1809, a deeper *Chandra* observation is needed, with Ch1 imaged close to the telescope’s optical axis.

Another plausible physical counterpart to HESS J1809 is

the J1809 pulsar/PWN. To date, young pulsars have been found in the vicinity of  $\sim 10$  extended TeV sources (e.g., de Jager 2006; Gallant 2007), and the likelihood of this happening by chance is very low (see, e.g., KPG07b). The ratio of the TeV flux of HESS J1809 to the X-ray flux of the J1809 PWN (including the outer component of the compact PWN) is about 100, higher than those observed in most TeV plerions (KPG07b). However, if one adds in the X-ray flux of the large-scale extended emission (§2.2.1), then the ratio decreases down to  $\sim 20$  (or even lower if one includes the diffuse emission of a larger extent, seen by ASCA; see Fig. 3c).

The center of the brightest part of HESS J1809 is offset from J1809 by  $\approx 8'$ , almost in the direction of the presumed pulsar motion. Such an offset is comparable to the  $10'–20'$  offsets found in most of TeV plerions (including the most secure associations PSR B0833–45/HESS J0835–455 [Vela] and PSR B1823–13/HESS J1825–137). An obvious explanation for such an offset is that the photons for the ICS are provided by a compact source (e.g., Source A) whose center lies at some distance from the pulsar ( $\geq 8d_{3.5}$  pc for Source A). Also, the offset might be due to the anisotropic supply of relativistic particles through the putative front jet (see §3.1.2).

If the TeV emission is produced by the ICS of an approximately uniform background radiation, such as the CMBR or Galactic starlight, then the origin of the offsets and the asymmetries of the extended X-ray and TeV PWN components could be attributed to the reverse SNR shock that had propagated through the nonhomogeneous SNR interior and reached one side of the PWN sooner than the other side, crushing the PWN and sweeping its contents along (Blondin et al. 2001). One can assume that the TeV source HESS J1809 is powered by this relic crushed PWN, whose relativistic electrons have not lost all their energy to synchrotron radiation because of, e.g., a lower magnetic field, while the compact PWN in the pulsar vicinity is created by fresh electrons, recently injected from the pulsar magnetosphere. As the electrons responsible for the TeV emission have been accumulating during a substantial fraction of the pulsar's lifetime, and the pulsar's spindown power was higher in the past, this hypothesis could explain the uncomfortably large ratio,  $\sim 0.01d_{3.5}^2$ , of the TeV luminosity to the *current* spindown power. (A similar explanation has been suggested by Aharonian et al. 2006 for the PSR B1823–13/HESS J1825–137 association.) This hypothesis can be tested with deep radio observations, which should be able to detect the synchrotron emission from the relic electrons of the crushed PWN.

In the above picture, the asymmetric extended X-ray emission south of the J1809 pulsar could also be associated with the crushed PWN and considered as an X-ray (synchrotron) counterpart of the TeV (IC) source HESS J1809. The small size of the extended X-ray emission, in comparison with the size of the TeV source, and its offset from the center of HESS J1809 could be attributed to the lower sensitivity of the ACIS chip S2 (where the central part of HESS J1809 is imaged – see Fig. 3a) or to a lower magnetic field in the central part. A deeper X-ray observation could distinguish between these two possibilities.

The large-scale morphology of the X-ray emission around J1809 is remarkably similar to that around PSR B1823–13, which powers the X-ray PWN G18.0–0.7 ( $L_X \sim 3 \times 10^{33}$  ergs  $s^{-1}$ , angular size  $\gtrsim 5'$ ; Gaensler et al. 2003). In addition to the extended low-surface-brightness component, the B1823–13 PWN has a much more compact ( $5''–10''$ ) brighter core, resolved by *Chandra* (Teter et al. 2004). The TeV emission

from HESS 1825–137 covers an area much larger than the X-ray PWN area, extending up to  $1^\circ$  southward from the pulsar (Aharonian et al. 2006). However, just as in the case of PSR J1809/HESS J1809, both the TeV and the low-surface-brightness X-ray emission have similar shapes, and they are offset in the same direction with respect to the pulsar position.

Finally, we would like to point out that there are two other young pulsars, J1811–1925 and J1809–1943, at distances of  $\approx 24'$  and  $\approx 19'$ , respectively, from the HESS J1809 center. PSR J1811–1925 can not be related to HESS J1809 since it has been associated with G11.2–0.3 (Kaspi et al. 2001), whose diameter,  $\approx 4'$ , is substantially smaller than the offset from HESS J1809. PSR J1809–1943 is the radio counterpart of the transient Anomalous X-ray Pulsar (AXP) XTE J1810–197 (Halpern et al. 2005, and references therein). Its association with HESS J1809 does not look very plausible because of the large spatial offset and because its properties are quite different from those of the young pulsars found in the vicinity of other TeV sources (no TeV emission from AXPs have been reported so far).

Thus, based on the current data, only two objects, the J1809 pulsar/PWN and, less likely, Ch1, are plausible candidates for the source of relativistic particles powering HESS J1809. In both cases, the TeV emission is generated by ICS of either IR photons from Source A (or Source B) or CMBR photons. To discriminate between different possibilities, the nature of Ch1 should be established in deep, high-resolution *Chandra* observations, and the extended X-ray PWN emission should be studied in a deep *XMM-Newton* exposure. The synchrotron emission from the alleged relic PWN could be detected in deep radio observations.

#### 4. CONCLUSION

We have detected the X-ray emission from PSR B1809–19 and its synchrotron nebula. The X-ray efficiency and spectrum of the PWN are similar to those of many other compact PWNe, both younger and older than J1809. The cometary shape of the compact PWN suggests that the pulsar is moving supersonically, but no extended tail is detected behind the pulsar, perhaps because the Mach number is not large enough or the exposure time is too short. Our analysis of the PWN morphology suggests an anisotropic pulsar wind outflow, possibly including jets oriented along the direction of pulsar motion. To establish the nature of the compact PWN unambiguously, proper motion measurements and a deeper *Chandra* observation are required.

The compact PWN is immersed in an extended emission of lower surface brightness. This extended emission is offset with respect to the pulsar in the direction opposite to that of the compact PWN (i.e. in the direction of the alleged proper motion). If the extended emission is indeed powered by the supersonically moving pulsar, then the radiating particles could be supplied through the front jet of the compact PWN or brought by the northern part of the reverse SNR shock that overtook the pulsar moving southward.

The spectrum of the pulsar can be described by a two-component BB+PL model. For reasonable  $n_H$  values, the parameters of this model and the corresponding component luminosities resemble those of Vela-like pulsars.

The J1809 pulsar and its PWN are located in the vicinity of the unidentified extended TeV source HESS J1809–193, which can be powered by ultrarelativistic electrons accelerated in the J1809 PWN. In addition to J1809, we found another X-ray source, Ch1, within the central part of

HESS J1809, which might also be an unresolved pulsar/PWN. Although the true nature of Ch1 remains elusive, we cannot rule out the possibility that Ch1 is an alternative X-ray counterpart of HESS J1809. Whatever of the two objects, J1809 or Ch1, supply the relativistic electrons, the TeV emission is likely produced by the ICS of either CMBR or IR photons from bright IRAS sources (Source A or Source B) projected near HESS J1809.

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